The study of hadron dynamics in relativistic heavy ion collisions

Venema, Lars Brent

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Chapter 6

Summary

6.1 Conclusions

In this thesis, pion emission patterns were studied in two reaction systems Ar + Ca and Au + Au at 1 GeV/u, with the aim to improve the understanding of the pion production in relativistic heavy ion collisions. The motivation came from the observations of concave pion spectra by Brockmann et al. [23] and Odyniec et al. [26] and from the resulting discussion about the observed shape. The study of the high energy tail of the π^0-momentum spectrum was regarded as promising because of its sensitivity to compression since it did not appear in small reaction systems.

Experiments were performed with TAPS together with the Forward Wall of the FoPi-collaboration at GSI. The combined measurement of charged particle multiplicities in the Forward Wall and the particles entering TAPS enabled an exclusive study of the pion production. TAPS was tested in separate experiments and its capabilities were demonstrated by measuring different reaction products, like photons, charged particles and neutrons. The data analysis involved new methods to treat the background contamination below the invariant mass peak of the π^0-meson due to the geometry of the detector and to perform particle identification in a high particle multiplicity environment.

The analysis of the data together with results from recent publications and theoretical models led to the following picture in the pion production during heavy ion collisions.

In heavy-ion collisions, pions are mainly produced via resonances [48]. Multiple scattering leads to a significant production of pions above the kinematical limit (cf. section 5.1.1). The mechanism to acquire energy above the kinematical limit probably involves heavier resonances than the $\Delta(1232)$ [102, 49]. This idea is supported by the observations that the spectra from theoretical models without the heavier resonances lack strength for the high momenta.

The reabsorption and rescattering cross-section for pions is large and only a small fraction of the pions observed are pions of the first generation, i.e. pion that after their production are never reabsorbed or rescattered. The interaction of the pions from a hot zone with the colder surrounding material cools the pion spectrum considerably. Possibly there is thermal equilibrium in the reaction zone, in the 'halo' (consisting of both the spectators and the 'corona' [9]) this is certainly not the case.

The pion emission pattern is not isotropic: high energy pions can only escape in the direction where the shadowing of colder matter is small, i.e. away from 'spectators'. This is both observed for the pion anti-flow [120, 121] and for the squeeze-out (cf. section 5.5).

Concerning the concave nature of the pion spectra, the following observations were made. The π^0-spectrum from the Ar + Ca reaction does not have a concave shape in contrast to the Au + Au spectrum. On basis of the experimental data presented in this thesis, the concaveness can originate from two sources: the geometrical size of the reaction system, which is in the heavier Au + Au reaction much larger and therefore more sensitive to the gradual cooling from the hot zone through the outer layers and, second, the Bose effect which is much more prominent in heavier reaction systems where the pion multiplicity is high.

The concaveness did not appear to be sensitive to impact parameter selections. This observation weakens the argument of the Bose enhancement, as the pion multiplicity is dependent on the number of participants in the reaction zone and thus on impact parameter. The fact that for the Au + Au reaction both slope parameters from the fit by equation 5.3 change, support the idea that the spectrum does not really consist of two slopes, but that equation 5.3 just is a nice parametrization of a concave spectrum [45].

According to the scaling proposed by Baldin and Stavinsky (cf. section 5.3), the low momentum part of the Au + Au π^0-spectrum should be considered as 'surprising' and *not* the high momentum part, because the tail of the spectrum nicely follows the scaling law of sub-threshold particle production in heavy-ion collisions.

The change in the overall slope of the π^0-spectra measured in the Au + Au reaction for the three impact parameter selections is well described by all the models. Apparently the difference observed in the experimental data is a purely geometrical effect and is not related to compressional effects, otherwise QGSM and RQMD would perform worse. The impact parameter dependence of the π^0-spectrum does not reveal any sensitivity to the density in the reaction zone.

The azimuthal pion distribution is anisotropic with respect to the reaction plane. A strong squeeze-out signal is measured in the π^0-data. Extensive checks were performed on the background to exclude systematic errors. The squeeze-out is observed in all theoretical models presented in this thesis, although the effect is much weaker in the theory. However, in the theoretical models there was no rapidity selection which certainly weakens the effect. The fact that the pion squeeze-out is observed in *all* theoretical models strongly supports the picture that it is caused by rescattering and not by compressional effects [124, 126, 125].

The squeeze-out is also observed for charged particles and neutrons. The strength of the squeeze-out is the same for both particle types as expected. In the lighter reaction system (Ar + Ca) the squeeze-out was absent, both for the charged particles and neutrons as for π^0-mesons. The flow signal for charged particles and neutrons in the Ar + Ca reaction is much weaker than the flow signal in the Au + Au reaction (reduction in S_1 approximately 50% for the lowest velocity selection). This fact points to an observable difference between Ar + Ca and Au + Au as reaction system. According to Qiubao Pan and P. Danielewicz, this is a consequence of compressibility [6].

Concerning the theoretical models the following remarks can be made. In general, all models are quite able to describe inclusive observables. However, some differences are striking. First, BUU seems to produce a fundamentally different shape of the spectrum.

It cannot be described by equation 5.1 with the same quality as spectra from the other models and experimental data. IQMD predicts far too 'cold' spectra. It is however very capable to predict the directed flows. It seems as if too much energy is put in the production of the collective effect and too little into the 'heating'.

The fact that the concave shape of the pion spectrum is present in IQMD and the resulting discussion about the origin of this second component, as can be found in [48], demonstrate the importance of the precise description of the Δ-resonance in the nuclear medium. It turns out that heavy ion collisions offer the possibility to study the dynamics of the resonances in the nuclear medium.

The absence of directivity ($\mathcal{D}$) in theoretical models without a density dependent potential clearly demonstrates that the flow effect is a consequence of repulsive forces (figure 5.17 in section 5.4.1), either due to compression or due to a large momentum difference between nucleons in the collision [95].

Model calculations have shown in section 5.2.3 that there is a strong correlation between the photon multiplicity measured in TAPS and the impact parameter of the collision. This observation is confirmed by the experimental data that show a strong correlation between the average charged particle multiplicity in the OPW and the photon multiplicity in TAPS. The advantage of this independent impact parameter selection is that the flow and particle distributions can be measured with a bias free selection.

The strength of the directed flow can be expressed by the vector $\vec{Q}$ (cf. equation 4.14). As is shown in the table 5.18) the squeeze-out shows a clear effect for a stronger selection on $||\vec{Q}||$. This fact can be used to amplify the squeeze-out in order to study the in-plane and the out-of-the reaction plane contribution separately.

The separation of the in-plane and the out-of-the reaction plane contribution to the pion spectrum is equivalent with the separation of a pion spectrum dominated by the cold 'spectator' zone from a spectrum dominated by the hot reaction zone. The reinteraction of the pions from the hot zone with the nucleons in the cold 'spectators' makes it clear that there will be a very gradual transition from hot matter in the center of the reaction zone to cold matter at the edges of the whole system.

6.2 Future Prospects

From the present investigation it follows that a very large amount of data need to be studied, like the application of a Bose thermal distribution to our data [127], the dependence of squeeze-out on the $||\vec{Q}||$-selection and the emission pattern in the OPW as function of photon multiplicity, including flow. A more exclusive analysis of the OPW will certainly increase the information content to a large extent and the combined analysis will be very interesting.

The magnitude of the squeeze-out for π^0-mesons turns out to be larger than found by the Kaos collaboration at GSI for the π^+-meson [116]. However, it is difficult to relate these data sets since the rapidity selection and the analysis method differ. This subject needs further investigation.

The π^0-spectrum has only been measured at midrapidity. Extending these measurements to other rapidity windows as well will open new opportunities to study the emission patterns of pions in relativistic heavy ion collisions. Especially, if this measurement can be performed for various rapidity windows questions about the influence of the pion flow on the squeeze-out can be addressed.

The scaling of Baldin (cf. section 5.3) needs further investigation. Different mass systems can be compared with the systematics and also the relative behaviour of the spectra needs attention. E.g. is the scaling of the spectra really understood and is it valid for all particles, like η, K, ω?

Concerning the theoretical models, heavier resonances should be included in the models to be able to describe the high energy pion production. Furthermore, the models without density dependent potentials are unable to predict the charged particle directivity. However, this density dependent potential may not lead to a reduced thermal excitation. It has to be investigated whether the momentum dependent repulsion can be responsible for an enhanced stiffness without reducing the particle production.

The availability of data from four theoretical models proved to be very helpful to understand the dynamical evolution in relativistic heavy ion physics. The possibility to apply the same experimental filter to the four sets of data offered excellent possibilities for comparison. Far more work in this direction can be done. The high quality set of theoretical predictions can also be used in the study for critical observables in future heavy ion experiments.

Appendi:

Relativist

This appendix covers s
extensive discussion ca
by Ole Hansen [128], a

A.1 Relativi

Our coordinate system
in the beam direction.
z-axis. Two reference f
lab-system, the target
a vector and the z-axis
vector into the xy-plan

As the initial momen
the total momentum of

and transverse moment

The transformations
mations of the parallel
linear and not transpar
make use of the variabl
rapidity (y) is defined a

where E is the total en